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6. AUTHOR(S)

Steven A. Orszag, Principal Investigator

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Program in Applied and Computational Mathematics
Princeton University
Princeton, NJ 08544-1000

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13. ABSTRACT (Maximum 200 words)

This report summarizes results published with support of this grant on renormalization group methods for large-eddy simulations (LES) of fluid flows, studies of the fundamental dynamics of compressible turbulence, development of methods to study strongly interacting vortices, methods to study intermittent probabilitt distributions in turbulence, and studies of dynamical issues involved in intermittent turbulence. Publications from 31 papers and 2 book chapter are summarized. The results demonstrate the utility of LES techniques, the differences between incompressible and compressible turbulence, and advanced models for small-scale structure that lead a series of surprising results, including a two-fluid model for small-scales in high Reynolds number turbulence.

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Final Technical Report

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In this work we have made significant progress on a number of key fluid dynamics problems. The major results include advanced renormalization group methods for large eddy simulations of flows and complex geometries, studies of fundamental dynamics of compressible turbulence, development of methods to study strongly interacting vortices, methods to study intermittent probability distributions in turbulence, and studies of dynamical issues involved in intermittent turbulence. Many of the results have been presented in publications. A brief description of each of these papers is given below:

1. Large-Eddy/RNG Simulation of Flow Over a Backward-Facing Step (G. Karniadakis, S. A. Orszag, V. Yakhot) to appear in Proc. of Turb. Modeling Conf., Dubrovnik, Editor W. Rodi (1990).

In this paper we combine spectral element methodology with a subgrid scale model based on renormalization (RNG) group theory to formulate an algorithm appropriate for simulating turbulent flows in complex geometries. The method is then applied to flow over a backward-facing step in transitional and turbulent flow regime. Preliminary results suggest that the RNG model can be applied faithfully even in the transitional and early turbulent regime, where other turbulence models fail.

2. Energy and Spectral Dynamics in Forced Compressible Turbulence (S. Kida and S. A. Orszag), J. Sci. Comp. 5, 85-125 (1990).

Numerical simulations are used to study compressible turbulence with micro-scale Reynolds numbers up to 40 and rms Mach numbers M up to 0.9. The flows are randomly forced, with energy supplied to either the rotational or compressive components of kinetic

energy, which is then transferred to internal energy through the pressure-dilatation interaction and viscous dissipation terms. Coupling between the two components of kinetic energy by the advection term is relatively weak, and most energy introduced to either component by the external force is transferred, without passing through the other component, to internal energy. A statistically quasi-equilibrium of kinetic energy is realized while internal energy increases steadily. The spectral form of the rotational component of velocity, which hardly depends on M, is very close to that for incompressible flow. On the other hand, the compressive component depends strongly on M especially at large wavenumbers.

3. Energy and Spectral Dynamics in Decaying Compressible Turbulence (S. Kida and S. A. Orszag), submitted (1990).

The statistical properties of decaying compressible turbulence are investigated by direct numerical simulations of flow in a periodic cube. Starting with fully developed turbulence for various micro-scale Reynolds numbers R_λ, rms Mach numbers M and small- and large-scale compressive ratios r_{CS} and r_{CL}, we find that the kinetic energy exhibits an exponential decay in time. Interactions between the compressive and rotational components of kinetic energy are weaker than self-interactions of the respective components. The energy spectrum of rotational component obeys the same Kolmogorov similarity law as for incompressible turbulence and forced compressible turbulence. The form of the energy spectrum of the compressive component, on the other hand, depends strongly on M. As the turbulence decays freely, R_λ and M decrease in time but r_{CS} and r_{CL} tend to some universal values.

4. Long-Time, Large-Scale Properties of a Randomly Stirred Compressible Fluid (I. Staroselsky, V. Yakhot, S. Kida, S. A. Orszag), Phys. Rev. Letters (July 9, 1990).

The large-scale, long-time properties of a compressible fluid stirred by a Gaussian random force with correlation $< f_i f_j > \propto k^{-y}$ are investigated. It is shown that when $\varepsilon = 4 + y - d > 3$ (d=space dimension) the effective sound velocity becomes scale-dependent in the limit $k \to 0$ and the fluid obeys a universal equation of state. The effective Mach number is also scale-dependent reaching a fixed point value $Ma*(k) < 1$ when $k \to 0$. The results of the theory are confirmed by direct numerical simulations.

5. Dynamical Aspects of Vortex Reconnection of Perturbed Anti-Parallel Vortex Tubes (M. J. Shelley, D. I. Meiron, S. A. Orszag), J. Fluid Mech., submitted (1990).

The phenomenon of vortex reconnection is analyzed numerically and the results are compared qualitatively with the predictions of a model of reconnection recently proposed by Saffman. Using spectral methods over both uniform and strained meshes, numerical simulations are performed of two nearly parallel, counter-rotating vortex tubes, over the range of Reynolds numbers $Re = 1000$–3500. We present results for the variation of the maximum of vorticity, the time to reconnection, and other diagnostics of this flow as functions of the Reynolds number. From numerical simulation of the model equations, we infer and demonstrate the existence of exact solutions to the model to which solutions arising from general initial conditions are attracted at late times. In the limit of infinite Reynolds number, the model predicts eventual saturation of the axial strain, a feature observed in the recent work of Pumir and Siggia and also observed in our full numerical simulations. In this respect the model captures the observed local dynamics of vortex stretching. Because the global effect of external flows are not included in the model, the axial strain eventually decays and the maximum vorticity grows linearly at late times. From the full numerical results, we see the possible emergence of the behavior of the axial strain at infinite Reynolds number. As our simulations are affected by nonlocal effects, we do observe saturation of the strain but no subsequent decay. It is also shown

analytically that the model predicts a reconnection time which varies logarithmically with increasing Reynolds number. Comparison with the full numerical simulation shows a much slower variation of the reconnection time with increasing Reynolds number than predicted by the model. Reconnection is also discussed from the point of view of its relation to the possible onset of nearly singular behavior of the Euler equation. In agreement with the recent numerical results of Pumir and Siggia, it appears that no singularity in the vorticity will form in a finite time for this class of flows.

6. Turbulence: Challenges for Theory and Experiment (U. Frisch and S. A. Orszag), Phys. Today, January 1990, 24-32 (1990).

High-Reynolds-number flows are ubiquitous. Although many aspects of such flows have been understood phenomenologically, a systematic theory of their detailed properties requires novel experiments.

7. Phenomenological Theory of Probability Distributions in Turbulence (V. Yakhot, S. A. Orszag, S. Balachandar, E. Jackson, Z.-S. She, L. Sirovich), J. Sci. Comp. **5**, No. 3, (1990).

A phenomenological theory of single-point probability distributions in turbulence is presented. Expressions for the probability distribution functions are derived and analyzed for a decaying passive scalar, temperature fluctuations in Bénard convection and vorticity fluctuations in both stationary and decaying homogeneous, isotropic turbulence. The predictions of the theory are compared with the results of physical and numerical experiments.

8. Intermittent Vortex Structures in Homogeneous Isotropic Turbulence (Z.-S. She, E. Jackson, S. A. Orszag), Nature, **344**, 226-228 (1990).

This paper reports numerical simulations which show that there are remarkably

simple spatial structures associated with intermittent regions of vorticity. In contrast to the classical description of turbulence as an array of 'pancake'- or 'lasagne'-like eddies, it is found that high-amplitude vortex structures are tube-like and that they generate local velocity fields that spiral around them.

9. Parallel Spectral Computations of Complex Engineering Flows (G. E. Karniadakis and S. A. Orszag), in Supercomputing in Engr. Analysis, (ed. by H. Adeli), New Generation Computing (1990).

This paper discusses the implementation of spectral element methods on parallel computers. Issues of code architecture, computer architecture, and code implementation are addressed in depth for both SIMD and MIMD computer architectures. Applications are described for both classes of computers.

10. Spectral Simulations of Complex Flows (G. E. Karniadakis and S. A. Orszag), in Proc. Sci. Engineering on Supercomputers, 5th Intl. Conf., London, pp. 1-34, Springer (1990).

In this paper multi-domain spectral element methods are discussed with application to the solution of fluid flows in complex geometries. Both high resolution direct and large-eddy simulations of complex geometry flows are illustrated. An efficient high-order accurate time-stepping method for incompressible flows is introduced. Examples of simulations of turbulence and simple geometries and of unsteady flows in complex geometries are given.

11. Intermittency of Turbulence (Z.-S. She and S. A. Orszag), in The Legacy of John von Neumann, Proc. of Symp. in Pure Math., SIAM, **50**, 197-211 (1990).

This paper investigates the nature of non-Gaussian statistics of turbulence by direct numerical simulations. It is shown that while large scale fluctuations are nearly

gaussian, small scale turbulence display a strongly non-Gaussian character. It is reported also that lateral velocity gradients are more intermittent than the longitudinal gradients, which is associated with the presence of flow structures aligned with the streamlines.

12. Vortex Structure and Dynamics in Turbulence (Z.-S. She and S. A. Orszag), in Proc. of the 1989 ICOSAHOM Conf., Torino, Italy, **80**, 173-183 (1990).

The dynamics of vortex structures in turbulence have been investigated statistically in pseudospectral numerical simulations of moderate Reynolds number turbulence. Coherent features of vortex stretching dynamics, as manifested in the alignment of the vorticity vector with a principal axis of the rate of strain, are investigated with an emphasis on their time development in turbulence decay from a random gaussian field. In addition, we have observed a tendency in developed turbulence for velocity vectors to lie in the plane formed by the two principal stretching directions. These phenomena provide a mechanism for depletion of nonlinearity in turbulence. The spatial and temporal coherence of vortex structures has been further studied using recently developed techniques which combine dynamical visualisation with statistical sampling analysis.

13. Statistical Aspects of Vortex Dynamics in Turbulence (Z.-S. She and S. A. Orszag), in Proc. of the 3d Annual Newport Conf. on Turbulence, Newport, RI, Springer-Verlag, (1990).

Coherent features of vortex structure and dynamics are investigated statistically in pseudo-spectral numerical simulations of moderate Reynolds number turbulence. The alignment of the vorticity vector with a principal axis of the rate of strain is investigated with an emphasis on its time development in turbulence decay from a random Gaussian field. In addition, a tendency in developed turbulence for velocity vectors to lie in a plane formed by the two principal stretching directions is reported, leading to an expla-

nation of depletion of nonlinearity in turbulence. The spatial and temporal coherence of vortex structures is further studied using recently developed techniques which combine dynamical visualisation with statistical sampling analysis.

14. Vortex Dynamics and Intermittency in Turbulence (Z.-S. She, E. Jackson, S. A. Orszag), Nonlinear World, Vol. 1., p. 693 (eds. Bar'yakhtar, Chernousenko, Erokhin, Sitenko, and Zakharov), World Sci. Publ. (1990).

Intermittency effects in turbulence are studied in the context of the dynamics of vortex structures. Direct visualization of turbulent flow fields shows that intermittent vortex structures are typically tube-like and that local flow structures are quasi-two dimensional. It is speculated that the Kelvin-Helmholtz instability is the typical dynamical mechanism leading to strong intermittency of small scales in turbulence.

15. Temporal Intermittency and Turbulence Production in the Kolmogorov Flow (Z.-S. She and B. Nicolaenko), IUTAM Symposium - Topological Fluid Mechanics, ed. Moffatt, Cambridge University Press, (1990).

This paper investigates the production of two-dimensional turbulence by a dynamical system approach. For the two-dimensional Kolmogorov flow, it is shown that strong turbulence is produced via intermittent temporal bursts, which corresponds to the situation where an unstable manifold embedding a homoclinic orbit intersects a weak chaotic state. The relevance of such symmetry-breaking homoclinic excursion to boundary layer turbulence is discussed.

16. On the PDF of Velocity Gradient in Fully Developed Turbulence (U. Frisch and Z.-S. She), Fluid Dynamics Research, **8**, 139-142 (1991).

A simple fluctuation argument à la Landau suggests why probability density functions of velocity gradients of turbulent velocity fields are often found to have a

close exponential tail. The detailed functional form depends on the assumptions made concerning the intermittency.

17. Exponential Attractors and their Relevance to Fluid Mechanics Systems (A. Eden, C. Foias, B. Nicolaenko and Z.-S. She), Physica D, in press (1992).

In this note we discuss some of the recent results in the mathematical theory of infinite dimensional dynamical systems as they pertain to some of the equations of fluid mechanics. Our main objective is to highlight the theory of exponential attractors and discuss its possible significance in the study of 2D incompressible N.S. equations.

18. Symmetry Breaking Homoclinic Chaos in the Kolmogorov Flow (B. Nicolaenko and Z.-S. She), Nonlinear World, Vol.1, (eds. Bar'yakhtar, Chernousenko, Erokhin, Sitenko and Zakharov), World Scientific Publ., 602 (1990).

The bursting regime of the Kolmogorov flow is described by persistent homoclinic cycles which are the direct sum of heteroclinic connections between multiple hyperbolic states. The hyperbolic states are invariant under a dihedral isotropy subgroup and are mapped into each other. Intermittent pulses correspond to trajectories within a small neighborhood of such heteroclinic connections, while weakly chaotic states stagnates near those hyperbolic points.

19. The Perfect Club Benchmarks: Effective Performance Evaluation of Supercomputers (S. A. Orszag, et al.), Intl. J. of Supercomputing Appl., **3**, 5-40 (1990).

This paper addresses computational issues including the generation of a new set of benchmarks for scientific computing.

20. Physical Model of Intermittency in Turbulence: Near-Dissipation-Range Non-Gaussian Statistics (Z.-S. She), Phys. Rev. Lett. **66** (5), 600-603 (1991).

We present a physical model constructed from the Navier-Stokes equation to describe the evolution of the probability distribution function of transverse velocity gradients in 3D isotropic turbulence. Quantitative agreement with data from direct numerical simulations of isotropic turbulence for a wide range of Reynolds number is obtained. The model is based on a concrete physical picture of self-distortion of structures and interaction between random eddies and structures; the dynamical balance explains the non-Gaussian equilibrium probability distributions.

21. Physical Model of Intermittency in Turbulence: Inertial-Range Non-Gaussian Statistics (Z.-S. She and S. A. Orszag), Phys. Rev. Lett., **66** (13), 1701-1704 (1991).

We present a physical model to describe the equilibrium probability distribution function (PDF) of velocity differences across an inertial-range distance in 3D isotropic turbulence. The form of the non-Gaussian PDF agrees well with data from direct numerical simulations. It is shown that these PDFs obey a self-similar property, and the resulting inertial-range exponents of high-order velocity structure functions are in agreement with both experimental and numerical data. The model suggests a physical explanation for the phenomenon of intermittency and the nature of multifractality in fully developed turbulence, namely, local self-distortion of turbulent structures.

22. A Case Study in Parallel Computing: Homogeneous Turbulence on a Hypercube (E. Jackson, Z.-S. She, and S. A. Orszag), J. Sci. Comp. **6** (1), 27-46 (1991).

In this article we discuss the detailed implementation of a parallel pseudospectral code for integration of the Navier-Stokes equations on an Intel iPSC/860 Hypercube. Issues related to the basic efficient parallelization of the algorithm on a hypercube are discussed, as well as optimization issues specific to the iPSC/860 system. With the combination of optimizations presented, the code runs on a 32-node iPSC/860 system

at a speed exceeding that of the fastest implementation on a Cray YMP by nearly 25%.

23. Mode Coupling in Nonlinear Rayleigh-Taylor Instability (D. Ofer, D. Shvarts, Z. Zinnamon, and S. A. Orszag), Phys. Fluids B., in press (1992).

This paper studies the interaction of a small number of modes i the two-fluid Rayleigh-Taylor instability at relatively late stages of development, i.e., the nonlinear regime, using a two-dimensional hydrodynamic code incorporating a front-tracking scheme. It is found that the interaction of modes can greatly affect the amount of mixing and may even reduce the width of the mixing region. This interaction is both relatively long range in wave-number space and also acts in both directions, i.e., short wavelengths affect long wavelengths and vice versa. Three distinct stages of interaction have been identified, including substantial interaction among modes some of which may still be in their classical (single mode) "linear" phase.

24. Challenges in Turbulence Research (F. Hussain, T. Kambe, K. Kuwahara, and S. A. Orszag), Fluid Dynamics Res. **7**, 51-63 (1991).

25. Structure and Dynamics of Homogeneous Turbulence: Models and Simulations (Z.-S. She, E. Jackson, and S. A. Orszag), Proc. Royal Soc. London A, 434, 101-124 (1991).

This paper presents a review of recent results on homogeneous turbulence. We discuss results obtained by direct numerical simulations as well as phenomenological models for the interpretation and understanding of these flows. In particular, we show that homogeneous turbulence can be well described in terms of a weakly correlated, random background field that is generally consistent with the classical Kolmogorov (1941) theory of turbulence, and strongly correlated, highly localized structures, that are largely responsible for so-called intermittency effects and deviations from Kolmogorov scaling. These results give a unified dynamical picture of turbulence that describes both the

energetics and intermittency in homogeneous turbulence, and allows us to develop a quantitative model for the description of the statistics of turbulence at small scales.

26. Renormalization Group Analysis of MHD Turbulence with Low Magnetic Reynolds Number (S. Sukoriansky, I. Staroselsky, B. Galperin, S. Roy, and S. A. Orszag), Progress Series of the Amer. Institute of Astronautics & Aeronautics, in press (1992).

The renormalization group (RNG) method is applied to study the two-dimensionalization of 3D Kolmogorov turbulence as a result of influence of the body force which selects some direction. On small scales we obtain a system of RNG equations for scale-dependent viscosity and the renormalized Joule dissipation time H^{-1}. Solving these equations we see the crossover from 3D to quasi-2D flow: when the wavenumber k approaches $k_* \propto \bar{\varepsilon}^{-1/2} H^{3/2}$ ($\bar{\varepsilon}$ is the viscous energy dissipation rate), the viscosity starts to deviate essentially from its isotropic behavior. We extend our analysis beyond the crossover region reformulating the problem in terms of the equation for vorticity. RNG analysis of large-scale properties of this equation shows that the scale-dependent renormalized viscosity $\nu(k)$ is positive and growing when k decreases. The renormalization of the value of Joule dissipation time in this range is absent. We obtain a fixed point of the RNG procedure corresponding to the self-similar regime with the energy spectrum $E(k) \propto k^{-3}$. The results are in a good agreement with the experimental data.

27. The Renormalization Group, the ε-Expansion and Derivation of Turbulence Models (V. Yakhot and L. M. Smith), J. Sci. Comp., **7** (1) (1992).

We reformulate the renormalization group (RNG) and the ε-expansion for derivation of turbulence models. The procedure is developed for the Navier-Stokes equations and the transport equations for the kinetic energy $\mathcal{K}$ and energy dissipation rate $\mathcal{E}$. The derivation draws in the works of Yakhot and Orszag (1986) and Smith and Reynolds

(1992), and all results are found at low order in the underlying perturbation expansion in powers of ε. The sum of the source terms in the $\mathcal{E}$-equation is known to be $O(1)$ due to the balance at leading order of $O(R_T^{1/2})$ terms. Smith and Reynolds (1992) showed the cancellation of some of the $O(R_T^{1/2})$ terms generated by the RNG procedure. Here we show that including the random-force contribution to $\mathcal{E}$-production results in the cancellation of *all* the $O(R_T^{1/2})$ terms. We find that two of the $O(1)$ terms in the RNG equation for the mean dissipation rate $\overline{\mathcal{E}}$ have the same form as those in the widely used model $\overline{\mathcal{E}}$-equation. The values of the coefficients of the familiar terms are close to those used in practice. An extra production term is predicted which is small for slow distortions, but important for rapid distortions. Hence, it may be a term that should be added to the $\overline{\mathcal{E}}$ model equation. We believe that the present derivation places the $\overline{\mathcal{E}}$ model equation on a more solid theoretical basis.

28. The 4/5 Kolmogorov Law for Stationary Turbulence: Application to High Rayleigh Number Benard Convection (V. Yakhot), Phys. Rev. Lett., July (1992).

29. Short Time Behavior of Eddy Viscosity Models (L. Smith and V. Yakhot), Fluid Dynamics Res., submitted (1992).

30. Flame Broadening Effects on Premixed Turbulent Flame Speed (P. D. Ronney and V. Yakhot), Combust. Sci. & Tech. (1991).

31. Hidden Conservation Laws in Hydrodynamics. Energy and Dissipation Rate Fluctuation Spectra in Strong Turbulence (V. Yakhot and V. Zakaharov), Physica D, submitted (1992).

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Proceedings of International Workshop on Large Eddy Simulation of Complex Engineering and Geophysical Flows (eds. B. Galperin and S. A. Orszag), Cambridge University Press, to appear (1992).

Parallel Spectral Computations of Complex Engineering Flows (G. E. Karniadakis and S. A. Orszag), in Supercomputing in Engr. Analysis, (ed. by H. Adeli) Decker, 289-324 (1991).